

# MHD Waves and Coronal Seismology: an overview of recent results

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Recent observations have revealed that MHD waves and oscillations are ubiquitous in the solar atmosphere, with a wide range of periods. We give a brief review of some aspects of MHD waves and coronal seismology which have recently been the focus of intense debate or are newly emerging. In particular, we focus on four topics: (i) the current controversy surrounding propagating intensity perturbations along coronal loops, (ii) the interpretation of propagating transverse loop oscillations, (iii) the ongoing search for coronal (torsional) Alfvén waves and (iv) the rapidly developing topic of quasi-periodic pulsations (QPP) in solar flares.

**Keywords:** MHD Waves, Coronal Seismology, Corona

## 1. Introduction

The study of MHD waves has two major applications within solar physics, namely, coronal (or magneto) seismology (Uchida 1970; Roberts *et al.* 1984) and the role of MHD waves in coronal heating. Both topics have been the subject of years of study. As MHD waves can carry magnetic energy over large distances, it was historically thought that they could play a major role in the heating of the solar atmosphere, especially in open field regions. However, a lack of actual observations in the solar atmosphere meant that, for a long time, studies of MHD waves were mainly theoretical. This situation has been changed dramatically over the last two decades with the advent of both imaging and spectroscopic instruments with high spatial and temporal resolution. Over the years, the observations have gradually revealed that waves and oscillations, which fall within the MHD spectrum, are present in most, if not all, coronal structures and that these waves can potentially provide a considerable part of the energy needed to heat the (quiet) solar corona and drive the solar wind. These observations have led to a rapid development of coronal seismology as well as renewed interest in the role of waves and oscillations in the heating of both open *and* closed field regions. Examples of both standing and propagating, slow and fast mode oscillations in coronal loops have been identified, as well as large-scale, global coronal perturbations.

To give a comprehensive overview of MHD waves, their role in coronal heating and the booming field of coronal seismology is impossible within this limited review. For comprehensive (recent) reviews on the subjects of coronal heating, we refer the

interested reader to e.g. Walsh & Ireland (2003); Erdélyi (2004); Ofman (2005); De Moortel *et al.* (2008) or Taroyan & Erdélyi (2009). Reviews of MHD waves and coronal seismology can be found in Nakariakov & Verwichte (2005); De Moortel (2005); Erdélyi (2006) or Banerjee *et al.* (2007), to name but a few. During 2009 and 2011, two *volumes* of Space Science Reviews were dedicated to detailed descriptions of various aspects of MHD wave propagation and coronal seismology. In this short paper, we will focus on topics which are presently most relevant, either because they are newly emerging or currently generating substantial debate. We will try to provide the reader with some context and outline the broad lines of the current thinking, rather than reporting details of individual studies. In particular, we will not include standing kink mode and standing slow mode oscillations of coronal loops (see Ruderman & Erdélyi 2009; Terradas 2009; Wang 2011), global coronal oscillations (see Wills-Davey & Attrill 2009; Gallagher & Long 2011) or oscillations in prominences (see Oliver 2009; Tripathi *et al.* 2009).

In Section 2, we focus on quasi-periodic perturbations propagating along coronal loops (the current flows vs waves debate), in Section 3 we highlight the recent results on Alfvénic, propagating waves and in Section 4, we discuss the current search for torsional (coronal) Alfvén waves. In Section 5 we summarise the currently emerging topic of QPP's. In Section 6 we highlight some recent developments in coronal seismology and conclude this review with a series of open questions.

## 2. Propagating Periodic Disturbances

Observations of disturbances traveling along coronal structures have been reported by a number of authors since 1999. However, recently the interpretation of these events as propagating slow magneto-acoustic waves has come under renewed scrutiny. For a more comprehensive description (especially of the earlier results), we refer the interested reader to the detailed reviews by De Moortel (2006, 2009) and Banerjee *et al.* (2011).

Reporting on the TRACE first results, Schrijver *et al.* (1999) describe “upward motions in the fans of 1MK loops in the outer envelope of the active-region corona.” These authors argue that the low propagation speed ( $\sim 40$  km/s) makes an interpretation in terms of (MHD) wave modes implausible but requires the presence of flows. A similar conclusion was reached by Winebarger *et al.* (2002). Following these initial reports, propagating disturbances were reported by a number of authors in both large coronal loops and (polar) plumes (see e.g. Berghmans & Clette 1999; De Moortel *et al.* 2000b; Ofman *et al.* 1997; Banerjee *et al.* 2000; O’Shea *et al.* 2006). Typically, the perturbations have amplitudes of a few percent of the background intensity, disappear below the noise level within a (coronal) gravitational scale height, display periods in the range of 2-10 minutes and velocities of the order of 100 km/s (see McEwan & De Moortel (2006)). It was the combination of these properties, but especially the apparent match with the local sound speed, that lead to the interpretation as propagating slow magneto-acoustic waves. Theoretical modelling (Nakariakov *et al.* 2000b; Tsiklauri & Nakariakov 2001; Ofman *et al.* 2000; De Moortel & Hood 2003, 2004; De Moortel *et al.* 2004) confirmed that the EUV imaging observations could be interpreted in terms of propagating slow magneto-acoustic waves, with thermal conduction proposed as the main damping mechanism and the quasi-periodic nature of the waves attributed to the leakage of p-modes from

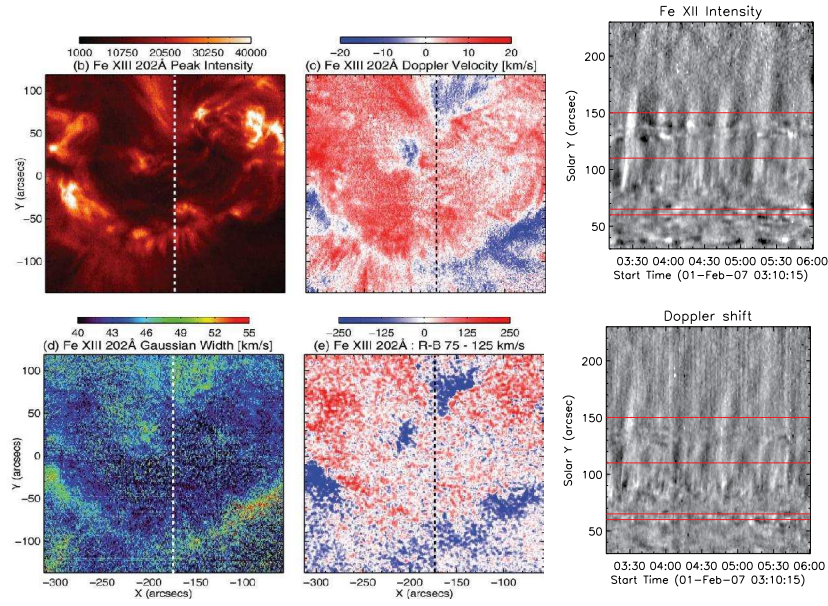


Figure 1. (Left) The region analysed by both De Pontieu & McIntosh (2010) and Wang *et al.* (2009b). Inferred single Gaussian fit parameters to the EIS spectroheliogram showing the peak intensity (panel (b)), (relative) Doppler velocity (panel (c)), Gaussian width (panel (d)), and the results of the 75-125 km/s R-B analysis in Fe XIII 202 Å (panel (e)) from De Pontieu & McIntosh (2010). On each of the panels the pointing of the time series is also shown (vertical dashed line). (Right) The upwardly-propagating waves in coronal loops observed by Hinode/EIS, reported by Wang *et al.* (2009b). (top) Time series of relative intensity along the slit in the Fe XII 195.12 Å line. (bottom) Time series of Doppler shift. Here the white color indicates the blueshift and the black color indicates the redshift.

the solar interior into the corona (De Pontieu *et al.* 2005; De Pontieu & Erdélyi 2006; De Moortel & Rosner 2007; Erdélyi *et al.* 2007; Malins & Erdélyi 2007). As this model could account for the major observational properties, it quickly became established as the prevalent interpretation.

Recently, the EUV imaging observations have been complimented by spectroscopic observations from Hinode/EIS and the picture has become considerably more complicated. The spectroscopic data show similar evidence of low amplitude, quasi-periodic oscillations not only in intensity but also in the Doppler velocity. However, the interpretation of the observed perturbations has (again) come into question. Some authors still favour the propagating slow magneto acoustic wave interpretation (Marsh *et al.* 2009; Banerjee *et al.* 2009b; Wang *et al.* 2009a,b; Kitagawa *et al.* 2010; Mariska & Muglach 2010; Krishna Prasad *et al.* 2011; Marsh *et al.* 2011; Wang *et al.* 2011) but other authors have interpreted quasi-periodic disturbances with very similar properties as (quasi-periodic) upflows (Sakao *et al.* 2007; Doschek *et al.* 2007, 2008; Del Zanna 2008; Harra *et al.* 2008; Hara *et al.* 2008; De Pontieu *et al.* 2009; McIntosh & De Pontieu 2009b,a; He *et al.* 2010; Guo *et al.* 2010; McIntosh *et al.* 2010; Peter 2010; Bryans *et al.* 2010; Tian *et al.* 2011; Ugarte-Urra & Warren 2011; Warren *et al.* 2011). Several papers have reported on quasi-periodically occurring

enhancements in the blue-wing of the spectral line profiles that are co-located with the propagating disturbances, with motions of the same order of magnitude. These enhancements are revealed when assessing the asymmetry, or fitting the lines with a double rather than a single Gaussian model. The need for a careful fitting of spectral lines using a double Gaussian model has recently been highlighted by several authors (e.g. Peter (2010)). Detailed analysis of spectroscopic line profiles by De Pontieu & McIntosh (2010) and Tian *et al.* (2011) shows that fitting line profiles which exhibit a quasi-periodically occurring excess in the blue wing with a single Gaussian will mimic the properties of the disturbances observed in the imaging data. However, an alternative interpretation of the quasi-periodically varying line profiles, again in terms of propagating slow waves, was put forward by Verwichte *et al.* (2010) and Wang *et al.* (2011), by suggesting that the (varying) double-Gaussian fit could consist of an oscillating dominant (core) component and an additional small, stationary blue-wing component.

Distinguishing between waves and flows is less straightforward than one might expect. It has become apparent that any distinguishing characteristics identified so far require extensive analysis of the spectroscopic and imaging data, complicated further by the low signal-to-noise ratio of these small amplitude perturbations. Therefore, it is not surprising that, at present, different authors reach different conclusions, even on the same datasets, as the observational signatures are difficult to disentangle (Verwichte *et al.* 2010; Peter 2010; De Pontieu & McIntosh 2010; Tian *et al.* 2011). Compare for example Wang *et al.* (2009*b*) and De Pontieu & McIntosh (2010), who both analyse the region shown in Fig. 1(left) in great detail, studying the intensity, Doppler velocity, line widths and line asymmetry in a variety of spectral lines. Fig. 1(right) (taken from Wang *et al.* (2009*b*)) shows the running difference plots, which are typically used to identify propagating disturbances in imaging data. Analysing spectroscopic EIS data, Wang *et al.* (2009*b*) find that the oscillations in intensity and Doppler shift are (approximately) in phase, which these authors interpret as evidence of propagating slow magneto acoustic waves. However performing further analysis on the same dataset, De Pontieu & McIntosh (2010) show that significant, in-phase, oscillations are found not only in the intensity and Doppler velocity, but also in the line widths and line asymmetries (see Fig. 2). These latter authors use modelling to show that such in-phase behaviour of oscillations in intensity, Doppler velocity, line widths and line asymmetries can be explained in terms of quasi-periodic upflows.

Regardless of the differing interpretations of the exact nature of these propagating disturbances, their quasi-periodicity has been clearly established. The periods of the observed perturbations are of the order of a few to ten minutes, a timescale which links them to the solar surface perturbations (p-modes) or convective buffeting (Fedun *et al.* 2009; Hansteen *et al.* 2010; Fedun *et al.* 2011). It is quite likely that the buffeting and tangling of the magnetic field by these solar (sub)surface perturbations will generate disturbances travelling along the magnetic field. However, a definitive identification of the driver has not been established. Also, it is unclear what the nature of these perturbations is (flows, waves, both or something entirely different?) and what happens to them as they travel through the solar atmosphere, although the similarity in properties hints at a close relation with chromospheric “Type II” spicules (De Pontieu *et al.* 2009; Rouppe van der Voort *et al.* 2009). These propagating disturbances have been linked with the mass cycle of the

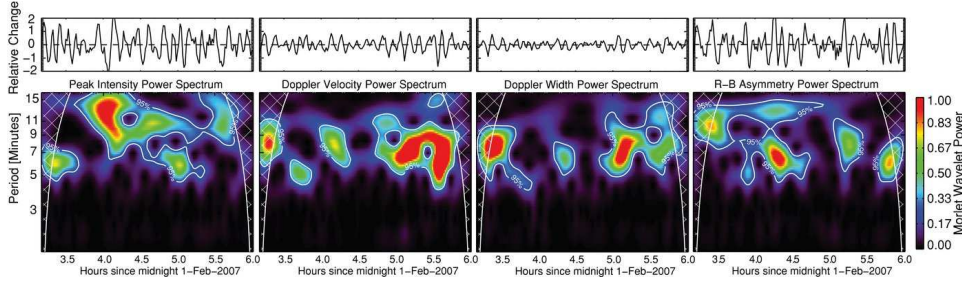


Figure 2. Wavelet power spectra for the Fe XIII 202 Å time series of De Pontieu & McIntosh (2010). The solid white contours denote regions of the wavelet power spectrum of 95% significance and the cross-hatched region encloses the cone-of-influence for the power spectrum.

solar corona and the solar wind (e.g. McIntosh & De Pontieu 2009b; McIntosh *et al.* 2010; De Pontieu *et al.* 2011) and it has been realised that despite their small amplitude, their omnipresence in the solar atmosphere could make them a significant player in the coronal energy budget. Very recent work by McIntosh *et al.* (2012) reports on slower, counterstreaming downflows ( $\sim 10$  km/s) in cooler lines, which the authors interpret as the return-flow of coronal material (i.e. the end of the mass cycle). In sunspots, recent numerical simulations of acoustic 3-min oscillations demonstrated that sunspot umbrae act as a non-ideal resonator, and that the leaky part of the oscillations naturally develops into the propagating waves in the corona Botha *et al.* 2011). Finally, we point out that the damping of the slow waves by thermal conduction also appears less robust than previously thought. Indeed, using an interpretation in terms of slow magneto-acoustic waves, Marsh *et al.* (2011) point out that for longer periods, thermal conduction cannot account for the observed rapid damping of the perturbations.

### 3. Propagating Transverse Loops Oscillations

Standing, transverse loop oscillations were one of the first examples of coronal loop oscillations to be observed and studied in great detail (see e.g. Nakariakov *et al.* 1999; Aschwanden *et al.* 2002; Schrijver *et al.* 2002). These oscillations, often observed to be generated by a nearby impulsive event, have generally been interpreted as (fast) kink mode oscillations (see Ruderman & Erdélyi 2009; Terradas 2009; Goossens *et al.* 2009 for a detailed review). Recently, there have been several reports in the literature of the observational detection of transverse perturbations, *propagating* along the magnetic field and localised in the transverse direction (Cirtain *et al.*, 2007; Okamoto *et al.*, 2007; Tomczyk *et al.*, 2007). These propagating displacements were detected with imaging instruments Hinode/SOT and Hinode/XRT in both cool and hot coronal structures, such as a prominence fibril (Okamoto *et al.*, 2007) and soft X-ray jets (Cirtain *et al.*, 2007), as well as in (chromospheric) spicules by De Pontieu *et al.* (2007) and He *et al.* (2009a,b) (see also Zaqarashvili & Erdélyi 2009). Similar perturbations were seen in large, off-limb, coronal loops by the Coronal Multi-Channel Polarimeter instrument (COMP) as periodic Doppler shifts (Tomczyk *et al.*, 2007) propagating along coronal magnetic field lines. As we are focusing this review on oscillations in coronal loops, we will

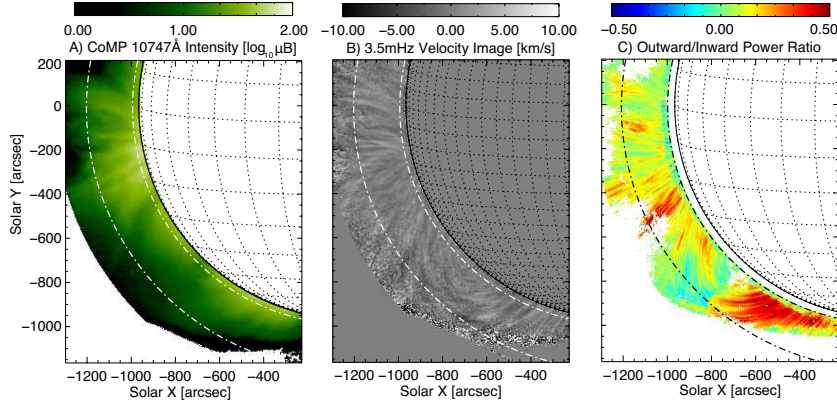


Figure 3. Snapshot of CoMP observations of time-averaged intensity (left), 3.5-mHz filtered Doppler velocity (middle) and power ratio map (right) taken from Tomczyk *et al.* 2007; Tomczyk & McIntosh 2009

only provide some detail of the COMP studies but the other observations have revealed largely similar properties.

The COMP observations (Tomczyk *et al.*, 2007; Tomczyk & McIntosh, 2009) indicate that the propagating transverse perturbations are, both spatially and temporally, ubiquitous in the solar corona. Fig. 3 shows a snapshot of the intensity, 3.5 mHz-filtered Doppler velocity and power ratio (i.e. outward power/inward power) observed by COMP. The waves were detected in time series of Doppler images but did not cause significant perturbations in intensity nor noticeable loop displacements, explaining why they have not been seen earlier by imaging instruments. The observed periods are of the order of several minutes, with a relatively broad power spectrum peaking at 5 minutes. This focus on 5 minute periods hints that the (footpoint) driving is likely to be related to the solar surface perturbations (p-modes). The propagation speed was estimated by Tomczyk & McIntosh (2009) to be of the order of 600 km/s. This is significantly higher than the local sound speed and places the observed propagation speeds in the range of the expected Alfvén speed. The observed speed is roughly constant in time, indicating that the structure supporting the oscillations (the wave guide) is relatively stable in time. The correlation analysis of Tomczyk *et al.* (2007), showed that the waves are indeed extended along the magnetic field, as the correlation length substantially exceeds the correlation width. Finally, there is a clear discrepancy between outward and inward power, with significant inward power only observed along shorter coronal loops (with footpoint separation  $< 300$  Mm). This indicates that the observed propagating perturbations are subject to considerable in-situ damping.

With speeds in the regions of the (estimated) local Alfvén speed, no evidence of significant intensity perturbations (and hence largely incompressible) and the apparent restoring force the magnetic tension, these observed propagating perturbations have characteristics which are Alfvénic in nature. Hence, they were originally interpreted as propagating (shear) Alfvén waves. Subsequent theoretical studies suggested a different interpretation of the observed displacements as propagating kink modes (Erdélyi & Fedun 2007; Van Doorsselaere *et al.* 2008*b,a*; Vasheghani Farahani *et al.* 2009). Indeed, the kink mode is locally a fast magne-



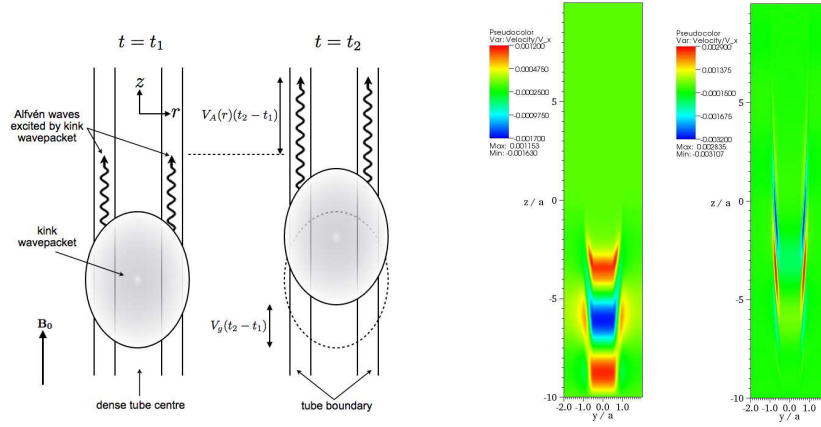


Figure 4. (left) Cartoon illustrating the process of mode coupling for a propagating, transverse footpoint motion, taken from Pascoe *et al.* (2011). (right) Snapshots of the transverse velocity (taken from Pascoe *et al.* 2010) at  $t = P$  and  $t = 5P$  for a density contrast  $\rho_0/\rho_e = 2$  and a boundary layer  $l/a = 0.5$ .

toacoustic wave, propagating obliquely to the magnetic field and guided along the field by a field-aligned plasma structure (a waveguide) by reflection or refraction (see e.g. Nakariakov *et al.* 1996). In the observations, the perturbed magnetic flux tube was displaced in the transverse direction as a whole, and the transverse size of the perturbation was at least an order of magnitude shorter than the wavelength along the field. In a 2D numerical study, Van Doorselaere *et al.* (2008a) pointed out the necessity for transverse structuring as without such a waveguiding field-aligned plasma non-uniformity, the perturbations would propagate not along the field, as observed, but across it. This is connected with the competition of two restoring forces, the magnetic tension force and the gradient of the total pressure.

The interpretation of the propagating transverse waves was clarified in recent 3D, full-MHD numerical simulations (Pascoe *et al.*, 2010, 2011). When (even very weak) transverse structuring is present (i.e. the loop is denser than the surrounding plasma), transverse footpoint motions generate an intrinsic coupling between the kink and (torsional) Alfvén modes. This process of mode coupling as the transverse footpoint motion propagates along the loop is similar to the process of resonant absorption in standing modes (see Goossens *et al.* 2011 for a review), as illustrated in Fig.4 (left); where the phase speed of the kink mode wave packet matches the local Alfvén speed, efficient mode coupling will occur (see e.g. Allan & Wright 2000) and energy is transferred rapidly from the transverse motion of the loop (the ‘kink’ mode) to the Alfvén mode, concentrated in the shell region of the loop. Hence, the kink mode can be thought of as a moving source of Alfvén waves. The (observable) transverse oscillation was found to decay in a few wave periods, which is consistent with observations. Fig.4 (right) shows the velocity perturbations after one and 5 periods, respectively. At the early stages of the simulation, just after one full cycle of the footpoint displacement has been completed, the (bulk) transverse oscillation is clearly visible. At later stages, it is clear that the only remaining perturbation is the perturbation in the shell region of the loop, which was identified by Pascoe *et al.* (2010) as an ( $m = 1$ ) Alfvén mode. In a follow-up paper, Pascoe *et al.* (2011)

demonstrate that although some density structuring has to be present to allow the mode coupling to take place, this structuring does not have to be regular (i.e. cylindrically symmetric) and the footpoint motion does not necessarily have to coincide exactly with the density enhancement which forms the loops.

Several authors have shown that the damping of the transverse motion is frequency-dependent. Focusing on the dominant frequency ( $\sim 3.5$  mHz) in the COMP observations, Pascoe *et al.* (2010) estimate the damping length of the propagating transverse wave packet as

$$L_d = V_g \tau \quad (3.1)$$

where  $V_g$  is the group speed of the wave packet and  $\tau$  is the damping time as given by

$$\tau = C \frac{a}{l} \frac{\rho_0 + \rho_e}{\rho_0 - \rho_e} P, \quad (3.2)$$

where  $a$  is the loop radius,  $l$  the thickness of the shell region,  $\rho_0$  and  $\rho_e$  are the internal and external densities, respectively and  $P$  is the period of the oscillations. The parameter  $C$  is a geometric parameter which depends on the specific form of the inhomogeneous layer (see Hollweg & Yang 1988; Goossens *et al.* 1992; Ruderman & Roberts 2002). Combining Eqns. (3.1) and (3.2), it is clear that

$$L_d \sim P, \quad (3.3)$$

i.e. the longer the period of the footpoint oscillations, the longer the damping length along the loop. Using this expression, Pascoe *et al.* (2010) find that this simple estimate of the damping length is qualitatively consistent with the COMP observation of Tomczyk & McIntosh (2009). They also show that the mode coupling process is very effective even for modest density contrasts (e.g.  $\rho_0/\rho_e = 2$ ) and quickly tends to an asymptotic value for  $\rho_0/\rho_e > 4$ . This frequency dependent damping is subsequently investigated further by Terradas *et al.* (2010) and Verth *et al.* (2010) who show that Eqn. (3.3) effectively leads to a frequency filtering: high-frequency oscillations will be damping faster (i.e. near the loop footpoints) whereas low-frequency oscillations will be able to propagate further along the loop. Verth *et al.* (2010) confirm this frequency filtering is present in the data, consolidating the interpretation of the COMP observations as a genuinely coupled kink-Alfvén (or ‘Alfvénic’) mode. However, it is important to understand that the coupling occurs only in the case of a smooth transverse profile of the plasma structuring, and does not appear when the boundary is a field-aligned discontinuity. Moreover, the *observed* (bulk) transverse waves correspond to the kink modes in the central part of the flux tube, while the induced Alfvén motions in the tube boundary (the shell region) are currently not resolved. Further recent investigations have focused on additional refinements of the basic model such as partial ionisation (Soler *et al.* 2011a), background flow (Soler *et al.* 2011b) and longitudinal stratification (Soler *et al.* 2011c). Partial ionisation and background flow are found to largely preserve the frequency-dependence in the amplitude decay induced by the mode coupling but longitudinal stratification introduces a more complex picture. Whereas mode coupling causes the amplitude to decrease, longitudinal (gravitational) stratification will cause a competing *increase* in the perturbation amplitudes. As the efficiency of the mode coupling process depends on the frequency, the resulting behaviour of the amplitude will depend on



whether the perturbation frequency falls below or above a critical value. This critical value of the frequency depends on the exact parameters of the model, such as the width of the inhomogeneous layer and the density contrast (see Eq. (52) of Soler *et al.* 2011c).

#### 4. The Search for (Torsional) Alfvén Waves

In a uniform medium with a straight magnetic field there are four kinds of MHD waves: slow and fast magnetoacoustic waves, the entropy wave and the Alfvén wave. The Alfvén wave is essentially incompressible, and its group speed is directed strictly parallel with the magnetic field. In non-uniform plasmas, Alfvén waves are situated at magnetic flux surfaces (surfaces of constant Alfvén speed). In this case, the coordinate along the flux surface plays the role of the ignorable coordinate. The presence of an ignorable, possibly curvilinear, coordinate is necessary, as the wave perturbations must keep the same distance between magnetic field lines. Otherwise, transverse perturbations cannot be incompressible. For example, in a plasma cylinder with a circular cross-section, the ignorable coordinate is the polar angle, and Alfvén waves are torsional (i.e. waves of magnetic twist and plasma rotation). The plasma displacement vector is also locally parallel to the flux surface. This means that Alfvén perturbations of neighbouring flux surfaces are disconnected from each other, and they do not constitute a collective mode, in contrast with magnetoacoustic modes of plasma structures. However, often coronal Alfvén waves are considered as locally plane, linearly-polarised in the transverse direction that represents the ignorable coordinate.

If the Alfvén speed varies across the magnetic field, Alfvén waves situated at different magnetic surfaces experience phase mixing, which leads to the creation of very sharp gradients in the transverse direction. In the presence of small, but finite viscosity or resistivity, these gradients can lead to enhanced dissipation of Alfvén waves. Consider a plane monochromatic Alfvén wave with frequency  $\omega$ , propagating in the  $z$  direction in a plasma with a 1D inhomogeneity in the Alfvén speed in the  $x$  direction,  $C_A(x)$ . In a developed stage of phase mixing (i.e. when gradients have developed sufficiently), the wave amplitude decays super-exponentially,

$$V_y(r) \propto \exp \left\{ -\frac{\nu\omega^2}{6C_A^5(x)} \left[ \frac{dC_A(x)}{dx} \right]^2 z^3 \right\}, \quad (4.1)$$

where  $\nu$  is the shear viscosity (Heyvaerts & Priest, 1983). Torsional waves are also subject to phase mixing, and equation (4.1) is applicable to them too.

When considering coronal Alfvén waves, especially in open magnetic structures, it is necessary to take into account vertical stratification. A plane linearly-polarised Alfvén wave with wavelength much shorter than the stratification scale height  $H$ , propagating upwards along a radially-directed magnetic field in an isothermal corona, is governed by the evolutionary equation

$$\frac{\partial V_y}{\partial r} - \frac{R_\odot^2}{4H} \frac{1}{r^2} V_y - \frac{1}{4C_A(C_A^2 - C_s^2)} \frac{\partial V_y^3}{\partial \tau} - \frac{\nu}{2C_A^3} \frac{\partial^2 V_y}{\partial \tau^2} = 0, \quad (4.2)$$

where  $r$  is the vertical coordinate,  $R_\odot$  is the radius of the Sun, and  $\tau$  is time (Nakariakov *et al.*, 2000a). The second term describes the change of amplitude

with height, the third describes nonlinear effects and the fourth the dissipation. The nonlinearity is connected with the modification of the Alfvén speed by the compressible flows induced by the Alfvén wave. In the derivation of this equation it was assumed that the nonlinear effects are weak, namely of the same order as the dissipative effects and the ratio of the wavelength to the density scale height. Only the lowest-order nonlinear terms were taken into account. The induced compressible perturbations have double the frequency of the inducing torsional wave. An important feature of the wave evolution in terms of this equation is the singularity at the height where the local Alfvén speed is equal to the sound speed. In the case of propagating weakly-nonlinear long-wavelength torsional waves, this singularity does not appear, since, in a flux tube, the nonlinearly induced compressible perturbation propagates at the sub-Alfvénic tube speed (Vasheghani Farahani *et al.*, 2011). Moreover, these waves do not modify the flux tube cross-section, as the centrifugal and magnetic tension forces, associated with the wave perturbations, cancel each other. This difference between torsional and plane Alfvén waves should be taken into account in 1D models of coronal Alfvén wave dynamics constructed for the study of coronal heating and solar wind acceleration problems (e.g. Suzuki & Inutsuka 2005; Murawski & Musielak 2010).

Vertical (field-aligned in open structures) stratification and a vertical change of the magnetic flux tube diameter modify the wave length and hence, affect the efficiency of Alfvén wave phase mixing (see, e.g. De Moortel *et al.* 2000a). Depending upon the specific geometry, the efficiency of wave damping can either increase or decrease compared to damping in a one-dimensional configuration. In particular, in the case of uniform density, exponentially diverging flux tubes, expression (4.1) was found to modify to an  $\exp(-\exp(z))$ -dependence (Ruderman *et al.*, 1998). In addition, the efficiency of phase mixing can be increased by nonlinear steepening (caused by the third term in Eq. (4.2), because of the decrease in wavelength (Ofman & Davila, 1998).

Although previous detections of Alfvén waves in the solar wind exist (see Ofman (2010) for a comprehensive review or Gosling *et al.* (2010) for some recent results) and there have been some reports in the recent literature on the possible detection of torsional Alfvén waves in the lower solar atmosphere (Jess *et al.* 2009), direct observational detection of torsional waves in the solar corona is still absent. As Alfvén waves are essentially incompressible, they cannot be detected with EUV or X-ray coronal imagers, and can be seen only with spectral instruments in those bands. In particular, in a number of studies, unresolved torsional waves were considered as the primary cause of non-thermal broadening of coronal emission lines. The broadening is associated with the Doppler shift caused by unresolved transverse motions of the plasma in the transverse direction. In contrast with kink modes, torsional Alfvén waves produce both red and blue Doppler shifts simultaneously, which leads to line broadening. For example, recent analysis of non-thermal broadening measured by Hinode/EIS demonstrated an increase in width of the Fe XII and Fe XIII lines in a polar region. The broadening was associated with a non-thermal line-of-sight velocity increase from  $26 \text{ km s}^{-1}$  at  $10''$  (i.e.  $\sim 7260 \text{ km}$ ) above the limb to  $42 \text{ km s}^{-1}$  some  $150''$  (i.e.  $\sim 110\,000 \text{ km}$ ) above the limb (Banerjee *et al.*, 2009a). Such behaviour is consistent with a growing Alfvén wave amplitude with height, described by the second term in equation (4.2). Thus, this analysis can be taken as indirect evidence of torsional waves in the corona. Similar evidence of accelerating propa-

gating disturbances was found by Gupta *et al.* (2010), analysing SOHO/SUMER and Hinode/EIS observations of an inter-plume region, who suggested these waves could be either Alfvénic or fast magnetoacoustic.

Another possibility for the detection of coronal Alfvén waves is open in the microwave band. As the wave changes the local direction of the magnetic field, it can lead to a modulation of the gyrosynchrotron emission (produced by non-thermal electrons accelerated in solar flares), which is sensitive to the angle between the magnetic field in the emitting plasma and the line-of-sight. Hence, in the presence of a torsional wave, the microwave emission can be periodically modulated. Evidence of this process was found by Grechnev *et al.* (2003) with the use of the Nobeyama Radioheliograph. However, the search for coronal Alfvén waves in the microwave band requires more attention.

## 5. Quasi-Periodic Pulsations

Oscillatory variations or quasi-periodic pulsations (QPP) of radio emission generated in solar flares have been investigated for several decades (see, e.g., Aschwanden 1987). The periodicities range from a fraction of a second to several minutes, and the modulation depth of the emission reaches 100%. Similar periodicities are often seen in hard X-rays (see Nakariakov & Melnikov (2009) for a review) and were recently found in gamma-rays (Nakariakov *et al.*, 2010a). There is growing evidence that QPP are a common and perhaps even intrinsic feature of solar flares: recent analysis of microwave emission generated in twelve similar single-loop flares showed that ten events (83%) had at least one or more significant spectral component with periods from 5–60 s (Kupriyanova *et al.*, 2010). Likewise, well-pronounced QPP have been found in radio, white-light and soft X-ray lightcurves of stellar flares (Mathioudakis *et al.*, 2003; Mitra-Kraev *et al.*, 2005). However, no systematic study of this phenomenon has been carried out.

In the context of MHD coronal seismology, flaring QPP are a very interesting subject. Firstly, the observed periods of QPP coincide with the periods of coronal waves and oscillations that are confidently interpreted in terms of MHD wave theory. Thus, QPP may well be the manifestation of coronal MHD oscillations, either modulating the emission directly, by changing the density, temperature and the absolute value or the direction of the magnetic field in the emitting plasma, or affecting the dynamics of the charged non-thermal particles (e.g., Zaitsev & Stepanov 2008), or periodically triggering magnetic reconnection and/or affecting the efficiency of the charged particle acceleration (Foullon *et al.* 2005; Chen & Priest 2006). A possible mechanism is the generation of anomalous resistivity by current-driven instabilities in current density spikes produced by magnetoacoustic waves in the vicinity of reconnection sites, which triggers magnetic reconnection.

Strong evidence supporting the connection of QPP with MHD oscillations is the observation of multiple periodicities, which may be associated with different spatial harmonics of MHD modes of oscillating structures. For example, the simultaneous presence of 28 s, 18 s, and 12 s oscillations was found in the microwave and hard X-ray emission in a flare (Inglis & Nakariakov, 2009). The ratio of the periods suggests that the oscillations are likely to be produced by different spatial harmonics of the highly-dispersive sausage mode.

Thus, the observation of QPP provides us with a powerful tool for the detection of MHD waves in coronal plasma structures and hence for MHD coronal seismology. The study of MHD oscillations in flaring emission has several advantages in the context of coronal seismology. In particular, as flares are the brightest events in solar physics, their observations can be of much higher cadence than the observations of the quiet corona. This allows one to achieve sub-second time resolution, which is, in particular, necessary for the detection of the fast-wave travel time across a coronal plasma structure. The latter time scale is needed for the diagnostics of fine transverse structuring of the corona (see, e.g., Nakariakov *et al.* 2005). Moreover, flaring energy releases are efficient drivers of MHD oscillations in the plasma structures around the flaring site, as the solar corona is a highly elastic and compressible medium. These oscillations, in turn, can modulate the flaring emission. This modulation can also be produced by MHD modes which have not been detected in the corona by other methods. For example the essentially incompressible torsional (or Alfvén) waves can modulate the efficiency of the gyrosynchrotron emission by changing the direction of the magnetic field to the line-of-sight (Grechnev *et al.*, 2003). Because of the strong dependence of the emission on the line-of-sight angle, the relative amplitude of the observed modulation can be several times higher than the amplitude of the wave, maximising the chances for its detection.

QPP can be produced not only by MHD oscillations, but may also directly result from oscillatory regimes of energy releases, e.g. periodic shedding of plasmoids (Kliem *et al.*, 2000) or over-stability of a current sheet with an externally generated steady flow (Ofman & Sui, 2006). Often oscillatory or quasi-oscillatory energy releases are observed in massive numerical simulations of MHD processes associated with solar flares (e.g. in experiments on magnetic flux emergence (Murray *et al.*, 2009)), where it is difficult to determine the cause of the oscillatory behaviour. This group of mechanisms for QPP is often referred to as a “dripping model” or “load/unload” (Nakariakov *et al.*, 2010*b*), as essentially it is based upon the conversion of a steady energy supply (e.g. the reconnecting plasma inflows) into a periodic energy release. Mathematically, it can be considered in terms of auto-oscillations of the dynamical system, such as limit cycles and relaxation oscillations. As the observed parameters (periods, amplitudes, signatures) of auto-oscillations are independent of the initial excitation and are determined by the parameters of the system only (in the case of periodic magnetic reconnection it could be the inflow rate, plasma resistivity and density, and the strength of the guiding field), their identification has very promising seismological potential which remains to be explored. One of the expected benefits is revealing the physical processes responsible for the magnetic energy release in flares, as the identification of the mechanisms for QPP puts additional constraints on the models of solar flares. Independently of the specific mechanism for the generation of QPP, their study opens up unique opportunities for seismology of stellar coronae.

A major recent avenue in the study of QPP is the investigation of their spatial structure with the use of X-ray imagers and microwave interferometers. Similarly to the morphology of the flares, QPP can appear either in a single loop geometry, when the hard X-ray sources are situated at the footpoints and sometimes at the loop apex (e.g. Inglis *et al.* 2008), while the microwave QPP occur in the legs of the loop (Kupriyanova *et al.*, 2010). Hard X-ray and microwaves QPP are usually

synchronous and hence are very likely produced by the same population of non-thermal electrons, accelerated in the energy release.

Another class of QPP is observed in two-ribbon flares, where the individual bursts of the emission come from different loops situated along a neutral line in the flaring arcade (see, e.g., Zimovets & Struminsky 2009). The speed of the energy release progression along the neutral line is typically a few tens km/s, which is at least an order of magnitude lower than the sound and Alfvén speeds. Very recently, this lower speed was shown to be consistent with the group speed of slow magnetoacoustic waves guided by an arcade (Nakariakov & Zimovets, 2011). In that model, a weakly oblique slow magnetoacoustic wave bounces between the arcade's footpoints and gradually progresses across the field. The highest value of the group speed occurs at a propagation angle of  $25^\circ$ – $28^\circ$  to the magnetic field. This effect can explain the temporal and spatial structure of quasi-periodic pulsations observed in two-ribbon flares: the sites of the energy releases gradually move along the axis of the arcade, across the magnetic field, at the group speed of the slow magnetoacoustic waves. The time between the individual bursts can be estimated as the slow wave travel time from the apex of the arcade to the footpoints and back, which is also consistent with observations. Another interesting topic is the generation of waves by flares. Parameters of these wave, in particular the periods, are determined by the parameters of the flares (see, e.g., Liu *et al.* 2011).

## 6. Discussion & Open Questions

After an initial period of very rapid growth following the launch of SOHO and TRACE in the late 1990's, coronal seismology is now going through a period of consolidating results and developing theoretical models to include more detailed structuring and additional physical processes, as well as incorporating new observational results from e.g. Hinode and SDO. The coronal flux tube model (Zajtsev & Stepanov 1975; Edwin & Roberts 1983) still forms the basis of much of the modelling and the interpretation of observed waves and oscillations. However, it is becoming evident that the simplified linear model must be extended considerably, taking into account realistic geometry, nonlinearity, and dissipation, so that coronal seismology can become a more accurate diagnostic tool. Again, a detailed description of all recent results is beyond the scope of this brief review so we highlight a few areas that have recently been reported in the literature.

Various aspect of both transverse and longitudinal fine-structuring have been investigated. The period-ratio  $P_1/2P_2$  has received a lot of attention, as its deviation from unity has implications for the longitudinal structuring of coronal loops and hence has potential as a seismological tool (see Andries *et al.* (2009) for a review and Macnamara & Roberts (2010, 2011) for more recent results). Whereas the modelling of the period ratio focuses on the effect of loop structuring on the temporal evolution of the wave modes, the spatial deformation of the mode and its seismological implications have also been studied (Erdélyi *et al.* 2007; Verth & Erdélyi 2008; Pascoe *et al.* 2009b; Verth *et al.* 2007, 2008, 2011). Most coronal loops are likely to be cooling as they are observed to oscillate, an aspect which had not previously been included in the modelling. A series of papers has recently studied how this cooling affects the damping rate of the oscillations (Morton & Erdélyi 2009, 2010; Morton *et al.* 2010; Ruderman 2011). Furthermore, numerical studies

have also started to focus on genuine 3D modelling of coronal loop oscillations (e.g. Pascoe *et al.* 2009*a*; Selwa *et al.* 2011*a,b*; Ofman 2009 for a review) and on the effect of the magnetic field structure, i.e. the magnetic topology, on the behaviour of MHD waves (e.g. McLaughlin *et al.* 2009; Selwa & Ofman 2010 and McLaughlin *et al.* (2011) for a review). Finally, we point out that efforts to refine the estimates of the coronal magnetic field and improve their accuracy are ongoing (Erdélyi & Taroyan 2008; De Moortel & Pascoe 2009; Verwichte *et al.* 2009; Terradas *et al.* 2011) and that a first attempt was made to estimate the adiabatic index using Hinode/EIS observations (Van Doorselaere *et al.*, 2011).

The topics we highlight in this review were chosen because they are currently receiving substantial attention in the literature, either as newly emerging observations of waves and oscillations or because the established interpretation is being challenged. Rather than providing a further summary, we conclude this review with a series of open questions for each of the four highlighted topics.

#### (a) *Quasi-periodic Propagating Disturbances*

- What is the root cause of the periodic disturbances (i.e. how are they generated) and what determines their observed speeds and periodicities?
- What are the observational signatures of waves and flows in the outer solar atmosphere; will we ever be able to discriminate or are both waves and flows present?
- If the propagating disturbances are flows, how can they propagate with a speed equal to the sound speed without forming shocks? If they are waves, is there clear evidence that the propagation speed corresponds to the local sound speed at all temperatures?
- Why are the propagating disturbances only seen for short distances along coronal structures? If they are waves, what is the relevant damping mechanism? If they are flows, what happens to the material?
- What role do these quasi-periodic propagating disturbances play in heating and/or mass loading of the outer solar atmosphere?

The waves and flows interpretations can each explain some of the observed properties, but neither can currently account for all of the observational signatures. As the observational data have been pushed to their (current) limits, progress might have to be made by studying realistic numerical models, combined with forward modelling to identify observable signatures for either, or both, interpretations.

#### (b) *Propagating Transverse Loop Oscillations*

- Are these waves truly ubiquitous, as they appear to be from recent observations and how are they generated?
- Can the Alfvén waves induced by the decaying kink waves through mode coupling in the loop boundary be observed?
- Can they really provide enough energy to heat the (quiet) solar corona and/or drive the solar wind?
- How can they be used as a seismological tool - i.e. what can we learn about the coronal plasma or loops from these observations? Current models strongly indicate

the presence of unresolved transverse structuring and hence we should be able to use the observed propagating transverse waves to probe the unresolved fine structure.

(c) *Torsional Alfvén Waves*

- Can we observe them directly with current or future missions (e.g. Solar Probe) or will we only be able to achieve indirect observations in the solar corona?
- Is the MHD description sufficient, or is the localisation of the theoretically predicted phase-mixed Alfvén perturbations more adequately described at the kinetic level?
- Can the waves tell us something about the field-aligned electric currents and hence be used to assess the relevance and precision of non-linear force-free magnetic field extrapolations and the amount of free magnetic energy available in active regions?

(d) *Quasi-periodic Pulsations (QPP)*

- What are they and how are they generated?
- Does the auto-oscillatory regime of magnetic reconnection really exist?
- What can QPP tell us about the physical conditions and processes operating in reconnection sites?
- Are QPP connected with MHD oscillations and waves in reconnection sites and what is the nature of this relationship? Can MHD scale waves affect local (dissipation scale) processes?

With the advent of SDO, providing high-resolution, full disk observations in a range of wavelengths, the number of observed waves and oscillations is bound to increase rapidly in the near future. This will allow coronal seismology to start making statistical studies to confirm the properties induced so far from a relatively small number of observations. At the same time, it will be crucial to combine this information gained from the imaging telescopes with spectroscopic observations, providing information about the local plasma, and to use the entire spectrum of wavelengths (e.g. radio) currently available through a combination of ground and space-based instrumentation. Finally, a two-pronged approach is needed on the modelling side; further refinement and in-depth study of the simple but informative basic models, combined with numerical simulations of realistic coronal (active region) configurations.

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## References

- Allan, W. & Wright, A. N. 2000 Magnetotail waveguide: Fast and Alfvén waves in the plasma sheet boundary layer and lobe. *J. Geophys. Res.*, **105**, 317–328. (doi:10.1029/1999JA900425)
- Andries, J., van Doorselaere, T., Roberts, B., Verth, G., Verwichte, E. & Erdélyi, R. 2009 Coronal Seismology by Means of Kink Oscillation Overtones. *Space Science Rev.*, **149**, 3–29. (doi:10.1007/s11214-009-9561-2)



- Aschwanden, M. J. 1987 Theory of radio pulsations in coronal loops. *Solar Phys.*, **111**, 113–136. (doi:10.1007/BF00145445)
- Aschwanden, M. J., de Pontieu, B., Schrijver, C. J. & Title, A. M. 2002 Transverse Oscillations in Coronal Loops Observed with TRACE II. Measurements of Geometric and Physical Parameters. *Solar Phys.*, **206**, 99–132. (doi:10.1023/A:1014916701283)
- Banerjee, D., Erdélyi, R., Oliver, R. & O’Shea, E. 2007 Present and Future Observing Trends in Atmospheric Magnetoseismology. *Solar Phys.*, **246**, 3–29. (doi:10.1007/s11207-007-9029-z)
- Banerjee, D., Gupta, G. R. & Teriaca, L. 2011 Propagating MHD Waves in Coronal Holes. *Space Science Rev.*, **158**, 267–288. (doi:10.1007/s11214-010-9698-z)
- Banerjee, D., O’Shea, E. & Doyle, J. G. 2000 Long-Period Oscillations in Polar Plumes as Observed by cds on Soho. *Solar Phys.*, **196**, 63–78.
- Banerjee, D., Pérez-Suárez, D. & Doyle, J. G. 2009a Signatures of Alfvén waves in the polar coronal holes as seen by EIS/Hinode. *Astron. Astrophys.*, **501**, L15–L18. (doi:10.1051/0004-6361/200912242)
- Banerjee, D., Teriaca, L., Gupta, G. R., Imada, S., Stenborg, G. & Solanki, S. K. 2009b Propagating waves in polar coronal holes as seen by SUMER & EIS. *Astron. Astrophys.*, **499**, L29–L32. (doi:10.1051/0004-6361/200912059)
- Berghmans, D. & Clette, F. 1999 Active region EUV transient brightenings - First Results by EIT of SOHO JOP80. *Solar Phys.*, **186**, 207–229.
- Botha, G. J. J., Arber, T. D., Nakariakov, V. M. & Zhugzhda, Y. D. 2011 Chromospheric Resonances above Sunspot Umbrae. *Astrophys.J.*, **728**, 84. (doi:10.1088/0004-637X/728/2/84)
- Bryans, P., Young, P. R. & Doschek, G. A. 2010 Multiple Component Outflows in an Active Region Observed with the EUV Imaging Spectrometer on Hinode. *Astrophys.J.*, **715**, 1012–1020. (doi:10.1088/0004-637X/715/2/1012)
- Chen, P. F. & Priest, E. R. 2006 Transition-Region Explosive Events: Reconnection Modulated by p-Mode Waves. *Solar Phys.*, **238**, 313–327. (doi:10.1007/s11207-006-0215-1)
- Cirtain, J. W., Golub, L., Lundquist, L., van Ballegoijen, A., Savcheva, A., Shimojo, M., DeLuca, E., Tsuneta, S., Sakao, T. *et al.* 2007 Evidence for Alfvén Waves in Solar X-ray Jets. *Science*, **318**, 1580–. (doi:10.1126/science.1147050)
- De Moortel, I. 2005 An overview of coronal seismology. *Royal Society of London Philosophical Transactions Series A*, **363**, 2743–2760. (doi:10.1098/rsta.2005.1665)
- De Moortel, I. 2006 Propagating magnetohydrodynamics waves in coronal loops. *Royal Society of London Philosophical Transactions Series A*, **364**, 461–472. (doi:10.1098/rsta.2005.1710)

- De Moortel, I. 2009 Longitudinal Waves in Coronal Loops. *Space Science Rev.*, **149**, 65–81. (doi:10.1007/s11214-009-9526-5)
- De Moortel, I., Browning, P., Bradshaw, S. J., Pintér, B. & Kontar, E. P. 2008 The way forward for coronal heating. *Astronomy and Geophysics*, **49**(3), 030 000–3. (doi:10.1111/j.1468-4004.2008.49321.x)
- De Moortel, I. & Hood, A. W. 2003 The damping of slow MHD waves in solar coronal magnetic fields. *Astron. Astrophys.*, **408**, 755–765. (doi:10.1051/0004-6361:20030984)
- De Moortel, I. & Hood, A. W. 2004 The damping of slow MHD waves in solar coronal magnetic fields. II. The effect of gravitational stratification and field line divergence. *Astron. Astrophys.*, **415**, 705–715. (doi:10.1051/0004-6361:20034233)
- De Moortel, I., Hood, A. W. & Arber, T. D. 2000a Phase mixing of Alfvén waves in a stratified and radially diverging, open atmosphere. *Astron. Astrophys.*, **354**, 334–348.
- De Moortel, I., Hood, A. W., Gerrard, C. L. & Brooks, S. J. 2004 The damping of slow MHD waves in solar coronal magnetic fields. III. The effect of mode coupling. *Astron. Astrophys.*, **425**, 741–752. (doi:10.1051/0004-6361:20040391)
- De Moortel, I., Ireland, J. & Walsh, R. W. 2000b Observation of oscillations in coronal loops. *Astron. Astrophys.*, **355**, L23–L26.
- De Moortel, I. & Pascoe, D. J. 2009 Putting Coronal Seismology Estimates of the Magnetic Field Strength to the Test. *Astrophys.J.*, **699**, L72–L75. (doi:10.1088/0004-637X/699/2/L72)
- De Moortel, I. & Rosner, R. 2007 An Estimate of P-Mode Damping by Wave Leakage. *Solar Phys.*, **246**, 53–63. (doi:10.1007/s11207-007-0392-6)
- De Pontieu, B. & Erdélyi, R. 2006 The nature of moss and lower atmospheric seismology. *Royal Society of London Philosophical Transactions Series A*, **364**, 383–394. (doi:10.1098/rsta.2005.1704)
- De Pontieu, B., Erdélyi, R. & De Moortel, I. 2005 How to Channel Photospheric Oscillations into the Corona. *Astrophys.J.*, **624**, L61–L64. (doi:10.1086/430345)
- De Pontieu, B., Hansteen, V. H., McIntosh, S. W. & Patsourakos, S. 2009 Estimating the Chromospheric Absorption of Transition Region Moss Emission. *Astrophys.J.*, **702**, 1016–1024. (doi:10.1088/0004-637X/702/2/1016)
- De Pontieu, B. & McIntosh, S. W. 2010 Quasi-periodic Propagating Signals in the Solar Corona: The Signature of Magnetoacoustic Waves or High-velocity Upflows? *Astrophys.J.*, **722**, 1013–1029. (doi:10.1088/0004-637X/722/2/1013)
- De Pontieu, B., McIntosh, S. W., Carlsson, M., Hansteen, V. H., Tarbell, T. D., Boerner, P., Martinez-Sykora, J., Schrijver, C. J. & Title, A. M. 2011 The Origins of Hot Plasma in the Solar Corona. *Science*, **331**, 55–. (doi:10.1126/science.1197738)

- De Pontieu, B., McIntosh, S. W., Carlsson, M., Hansteen, V. H., Tarbell, T. D., Schrijver, C. J., Title, A. M., Shine, R. A., Tsuneta, S. *et al.* 2007 Chromospheric Alfvénic Waves Strong Enough to Power the Solar Wind. *Science*, **318**, 1574–. (doi:10.1126/science.1151747)
- Del Zanna, G. 2008 Flows in active region loops observed by Hinode EIS. *Astron. Astrophys.*, **481**, L49–L52. (doi:10.1051/0004-6361:20079087)
- Doschek, G. A., Mariska, J. T., Warren, H. P., Brown, C. M., Culhane, J. L., Hara, H., Watanabe, T., Young, P. R. & Mason, H. E. 2007 Nonthermal Velocities in Solar Active Regions Observed with the Extreme-Ultraviolet Imaging Spectrometer on Hinode. *Astrophys.J.*, **667**, L109–L112. (doi:10.1086/522087)
- Doschek, G. A., Warren, H. P., Mariska, J. T., Muglach, K., Culhane, J. L., Hara, H. & Watanabe, T. 2008 Flows and Nonthermal Velocities in Solar Active Regions Observed with the EUV Imaging Spectrometer on Hinode: A Tracer of Active Region Sources of Heliospheric Magnetic Fields? *Astrophys.J.*, **686**, 1362–1371. (doi:10.1086/591724)
- Edwin, P. M. & Roberts, B. 1983 Wave propagation in a magnetic cylinder. *Solar Phys.*, **88**, 179–191. (doi:10.1007/BF00196186)
- Erdélyi, R. 2004 Coronal heating: Heating in the solar atmosphere. *Astronomy and Geophysics*, **45**(4), 040 000–4. (doi:10.1046/j.1468-4004.2003.45434.x)
- Erdélyi, R. 2006 Magnetic coupling of waves and oscillations in the lower solar atmosphere: can the tail wag the dog? *Royal Society of London Philosophical Transactions Series A*, **364**, 351–381. (doi:10.1098/rsta.2005.1703)
- Erdélyi, R. & Fedun, V. 2007 Are There Alfvén Waves in the Solar Atmosphere? *Science*, **318**, 1572–. (doi:10.1126/science.1153006)
- Erdélyi, R., Malins, C., Tóth, G. & de Pontieu, B. 2007 Leakage of photospheric acoustic waves into non-magnetic solar atmosphere. *Astron. Astrophys.*, **467**, 1299–1311. (doi:10.1051/0004-6361:20066857)
- Erdélyi, R. & Taroyan, Y. 2008 Hinode EUV spectroscopic observations of coronal oscillations. *Astron. Astrophys.*, **489**, L49–L52. (doi:10.1051/0004-6361:200810263)
- Fedun, V., Erdélyi, R. & Shelyag, S. 2009 Oscillatory Response of the 3D Solar Atmosphere to the Leakage of Photospheric Motion. *Solar Phys.*, **258**, 219–241. (doi:10.1007/s11207-009-9407-9)
- Fedun, V., Shelyag, S. & Erdélyi, R. 2011 Numerical Modeling of Footpoint-driven Magneto-acoustic Wave Propagation in a Localized Solar Flux Tube. *Astrophys.J.*, **727**, 17. (doi:10.1088/0004-637X/727/1/17)
- Foullon, C., Verwichte, E., Nakariakov, V. M. & Fletcher, L. 2005 X-ray quasi-periodic pulsations in solar flares as magnetohydrodynamic oscillations. *Astron. Astrophys.*, **440**, L59–L62. (doi:10.1051/0004-6361:200500169)

- Gallagher, P. T. & Long, D. M. 2011 Large-scale Bright Fronts in the Solar Corona: A Review of "EIT waves". *Space Science Rev.*, **158**, 365–396. (doi:10.1007/s11214-010-9710-7)
- Goossens, M., Erdélyi, R. & Ruderman, M. S. 2011 Resonant MHD Waves in the Solar Atmosphere. *Space Science Rev.*, **158**, 289–338. (doi:10.1007/s11214-010-9702-7)
- Goossens, M., Hollweg, J. V. & Sakurai, T. 1992 Resonant behaviour of MHD waves on magnetic flux tubes. III - Effect of equilibrium flow. *Solar Phys.*, **138**, 233–255. (doi:10.1007/BF00151914)
- Goossens, M., Terradas, J., Andries, J., Arregui, I. & Ballester, J. L. 2009 On the nature of kink MHD waves in magnetic flux tubes. *Astron. Astrophys.*, **503**, 213–223. (doi:10.1051/0004-6361/200912399)
- Gosling, J. T., Teh, W.-L. & Eriksson, S. 2010 A Torsional Alfvén Wave Embedded Within a Small Magnetic Flux Rope in the Solar Wind. *Astrophys.J.*, **719**, L36–L40. (doi:10.1088/2041-8205/719/1/L36)
- Grechnev, V. V., White, S. M. & Kundu, M. R. 2003 Quasi-periodic Pulsations in a Solar Microwave Burst. *Astrophys.J.*, **588**, 1163–1175. (doi:10.1086/374315)
- Guo, L.-J., Tian, H. & He, J.-S. 2010 Quasi-periodic outflows observed by the X-Ray Telescope onboard Hinode in the boundary of an active region. *Research in Astronomy and Astrophysics*, **10**, 1307–1314. (doi:10.1088/1674-4527/10/12/011)
- Gupta, G. R., Banerjee, D., Teriaca, L., Imada, S. & Solanki, S. 2010 Accelerating Waves in Polar Coronal Holes as Seen by EIS and SUMER. *Astrophys.J.*, **718**, 11–22. (doi:10.1088/0004-637X/718/1/11)
- Hansteen, V. H., Hara, H., De Pontieu, B. & Carlsson, M. 2010 On Redshifts and Blueshifts in the Transition Region and Corona. *Astrophys.J.*, **718**, 1070–1078. (doi:10.1088/0004-637X/718/2/1070)
- Hara, H., Watanabe, T., Harra, L. K., Culhane, J. L., Young, P. R., Mariska, J. T. & Doschek, G. A. 2008 Coronal Plasma Motions near Footpoints of Active Region Loops Revealed from Spectroscopic Observations with Hinode EIS. *Astrophys.J.*, **678**, L67–L71. (doi:10.1086/588252)
- Harra, L. K., Sakao, T., Mandrini, C. H., Hara, H., Imada, S., Young, P. R., van Driel-Gesztelyi, L. & Baker, D. 2008 Outflows at the Edges of Active Regions: Contribution to Solar Wind Formation? *Astrophys.J.*, **676**, L147–L150. (doi:10.1086/587485)
- He, J., Marsch, E., Tu, C. & Tian, H. 2009a Excitation of Kink Waves Due to Small-Scale Magnetic Reconnection in the Chromosphere? *Astrophys.J.*, **705**, L217–L222. (doi:10.1088/0004-637X/705/2/L217)
- He, J.-S., Marsch, E., Tu, C.-Y., Guo, L.-J. & Tian, H. 2010 Intermittent outflows at the edge of an active region - a possible source of the solar wind? *Astron. Astrophys.*, **516**, A14. (doi:10.1051/0004-6361/200913712)

- He, J.-S., Tu, C.-Y., Marsch, E., Guo, L.-J., Yao, S. & Tian, H. 2009*b* Upward propagating high-frequency Alfvén waves as identified from dynamic wave-like spicules observed by SOT on Hinode. *Astron. Astrophys.*, **497**, 525–535. (doi:10.1051/0004-6361/200810777)
- Heyvaerts, J. & Priest, E. R. 1983 Coronal heating by phase-mixed shear Alfvén waves. *Astron. Astrophys.*, **117**, 220–234.
- Hollweg, J. V. & Yang, G. 1988 Resonance absorption of compressible magnetohydrodynamic waves at thin 'surfaces'. *J. Geophys. Res.*, **93**, 5423–5436. (doi:10.1029/JA093iA06p05423)
- Inglis, A. R. & Nakariakov, V. M. 2009 A multi-periodic oscillatory event in a solar flare. *Astron. Astrophys.*, **493**, 259–266. (doi:10.1051/0004-6361:200810473)
- Inglis, A. R., Nakariakov, V. M. & Melnikov, V. F. 2008 Multi-wavelength spatially resolved analysis of quasi-periodic pulsations in a solar flare. *Astron. Astrophys.*, **487**, 1147–1153. (doi:10.1051/0004-6361:20079323)
- Jess, D. B., Mathioudakis, M., Erdélyi, R., Crockett, P. J., Keenan, F. P. & Christian, D. J. 2009 Alfvén Waves in the Lower Solar Atmosphere. *Science*, **323**, 1582–. (doi:10.1126/science.1168680)
- Kitagawa, N., Yokoyama, T., Imada, S. & Hara, H. 2010 Mode Identification of MHD Waves in an Active Region Observed with Hinode/EIS. *Astrophys.J.*, **721**, 744–749. (doi:10.1088/0004-637X/721/1/744)
- Kliem, B., Karlický, M. & Benz, A. O. 2000 Solar flare radio pulsations as a signature of dynamic magnetic reconnection. *Astron. Astrophys.*, **360**, 715–728.
- Krishna Prasad, S., Banerjee, D. & Gupta, G. R. 2011 Propagating intensity disturbances in polar corona as seen from AIA/SDO. *Astron. Astrophys.*, **528**, L4. (doi:10.1051/0004-6361/201016405)
- Kupriyanova, E. G., Melnikov, V. F., Nakariakov, V. M. & Shibasaki, K. 2010 Types of Microwave Quasi-Periodic Pulsations in Single Flaring Loops. *Solar Phys.*, **267**, 329–342. (doi:10.1007/s11207-010-9642-0)
- Liu, W., Title, A. M., Zhao, J., Ofman, L., Schrijver, C. J., Aschwanden, M. J., De Pontieu, B. & Tarbell, T. D. 2011 Direct Imaging of Quasi-periodic Fast Propagating Waves of  $\sim 2000 \text{ km s}^{-1}$  in the Low Solar Corona by the Solar Dynamics Observatory Atmospheric Imaging Assembly. *Astrophys.J.*, **736**, L13. (doi:10.1088/2041-8205/736/1/L13)
- Macnamara, C. K. & Roberts, B. 2010 Effects of thermal conduction and compressive viscosity on the period ratio of the slow mode. *Astron. Astrophys.*, **515**, A41. (doi:10.1051/0004-6361/200913409)
- Macnamara, C. K. & Roberts, B. 2011 The period ratio for kink and sausage modes in a magnetic slab. *Astron. Astrophys.*, **526**, A75. (doi:10.1051/0004-6361/201015460)

- Malins, C. & Erdélyi, R. 2007 Direct Propagation of Photospheric Acoustic p Modes into Nonmagnetic Solar Atmosphere. *Solar Phys.*, **246**, 41–52. (doi:10.1007/s11207-007-9073-8)
- Mariska, J. T. & Muglach, K. 2010 Doppler-shift, Intensity, and Density Oscillations Observed with the Extreme Ultraviolet Imaging Spectrometer on Hinode. *Astrophys.J.*, **713**, 573–583. (doi:10.1088/0004-637X/713/1/573)
- Marsh, M. S., De Moortel, I. & Walsh, R. W. 2011 Observed Damping of the Slow Magnetoacoustic Mode. *Astrophys.J.*, **734**, 81. (doi:10.1088/0004-637X/734/2/81)
- Marsh, M. S., Walsh, R. W. & Plunkett, S. 2009 Three-dimensional Coronal Slow Modes: Toward Three-dimensional Seismology. *Astrophys.J.*, **697**, 1674–1680. (doi:10.1088/0004-637X/697/2/1674)
- Mathioudakis, M., Seiradakis, J. H., Williams, D. R., Avgoloupis, S., Bloomfield, D. S. & McAteer, R. T. J. 2003 White-light oscillations during a flare on II Peg. *Astron. Astrophys.*, **403**, 1101–1104. (doi:10.1051/0004-6361:20030394)
- McEwan, M. P. & De Moortel, I. 2006 Longitudinal intensity oscillations observed with TRACE: evidence of fine-scale structure. *Astron. Astrophys.*, **448**, 763–770. (doi:10.1051/0004-6361:20054041)
- McIntosh, S. W. & De Pontieu, B. 2009a High-Speed Transition Region and Coronal Upflows in the Quiet Sun. *Astrophys.J.*, **707**, 524–538. (doi:10.1088/0004-637X/707/1/524)
- McIntosh, S. W. & De Pontieu, B. 2009b Observing Episodic Coronal Heating Events Rooted in Chromospheric Activity. *Astrophys.J.*, **706**, L80–L85. (doi:10.1088/0004-637X/706/1/L80)
- McIntosh, S. W., Innes, D. E., de Pontieu, B. & Leamon, R. J. 2010 STEREO observations of quasi-periodically driven high velocity outflows in polar plumes. *Astron. Astrophys.*, **510**, L2. (doi:10.1051/0004-6361/200913699)
- McIntosh, S. W., Tian, H., Sechler, M. & De Pontieu, B. 2012 ???? *Astrophys. J. Lett.*, p. submitted.
- McLaughlin, J. A., De Moortel, I., Hood, A. W. & Brady, C. S. 2009 Nonlinear fast magnetoacoustic wave propagation in the neighbourhood of a 2D magnetic X-point: oscillatory reconnection. *Astron. Astrophys.*, **493**, 227–240. (doi:10.1051/0004-6361:200810465)
- McLaughlin, J. A., Hood, A. W. & de Moortel, I. 2011 Review Article: MHD Wave Propagation Near Coronal Null Points of Magnetic Fields. *Space Science Rev.*, **158**, 205–236. (doi:10.1007/s11214-010-9654-y)
- Mitra-Kraev, U., Harra, L. K., Williams, D. R. & Kraev, E. 2005 The first observed stellar X-ray flare oscillation: Constraints on the flare loop length and the magnetic field. *Astron. Astrophys.*, **436**, 1041–1047. (doi:10.1051/0004-6361:20052834)

- Morton, R. J. & Erdélyi, R. 2009 Transverse Oscillations of a Cooling Coronal Loop. *Astrophys.J.*, **707**, 750–760. (doi:10.1088/0004-637X/707/1/750)
- Morton, R. J. & Erdélyi, R. 2010 Application of the theory of damping of kink oscillations by radiative cooling of coronal loop plasma. *Astron. Astrophys.*, **519**, A43. (doi:10.1051/0004-6361/201014504)
- Morton, R. J., Hood, A. W. & Erdélyi, R. 2010 Propagating magneto-hydrodynamic waves in a cooling homogenous coronal plasma. *Astron. Astrophys.*, **512**, A23. (doi:10.1051/0004-6361/200913365)
- Murawski, K. & Musielak, Z. E. 2010 Linear Alfvén waves in the solar atmosphere. *Astron. Astrophys.*, **518**, A37. (doi:10.1051/0004-6361/201014394)
- Murray, M. J., van Driel-Gesztelyi, L. & Baker, D. 2009 Simulations of emerging flux in a coronal hole: oscillatory reconnection. *Astron. Astrophys.*, **494**, 329–337. (doi:10.1051/0004-6361:200810406)
- Nakariakov, V. M., Foullon, C., Myagkova, I. N. & Inglis, A. R. 2010a Quasi-Periodic Pulsations in the Gamma-Ray Emission of a Solar Flare. *Astrophys.J.*, **708**, L47–L51. (doi:10.1088/2041-8205/708/1/L47)
- Nakariakov, V. M., Inglis, A. R., Zimovets, I. V., Foullon, C., Verwichte, E., Sych, R. & Myagkova, I. N. 2010b Oscillatory processes in solar flares. *Plasma Physics and Controlled Fusion*, **52**(12), 124009. (doi:10.1088/0741-3335/52/12/124009)
- Nakariakov, V. M. & Melnikov, V. F. 2009 Quasi-Periodic Pulsations in Solar Flares. *Space Science Rev.*, **149**, 119–151. (doi:10.1007/s11214-009-9536-3)
- Nakariakov, V. M., Ofman, L. & Arber, T. D. 2000a Nonlinear dissipative spherical Alfvén waves in solar coronal holes. *Astron. Astrophys.*, **353**, 741–748.
- Nakariakov, V. M., Ofman, L., Deluca, E. E., Roberts, B. & Davila, J. M. 1999 TRACE observation of damped coronal loop oscillations: Implications for coronal heating. *Science*, **285**, 862–864. (doi:10.1126/science.285.5429.862)
- Nakariakov, V. M., Pascoe, D. J. & Arber, T. D. 2005 Short Quasi-Periodic MHD Waves in Coronal Structures. *Space Science Rev.*, **121**, 115–125. (doi:10.1007/s11214-006-4718-8)
- Nakariakov, V. M., Roberts, B. & Mann, G. 1996 MHD modes of solar wind flow tubes. *Astron. Astrophys.*, **311**, 311–316.
- Nakariakov, V. M. & Verwichte, E. 2005 Coronal Waves and Oscillations. *Living Reviews in Solar Physics*, **2**, 3.
- Nakariakov, V. M., Verwichte, E., Berghmans, D. & Robbrecht, E. 2000b Slow magnetoacoustic waves in coronal loops. *Astron. Astrophys.*, **362**, 1151–1157.
- Nakariakov, V. M. & Zimovets, I. V. 2011 Slow Magnetoacoustic Waves in Two-ribbon Flares. *Astrophys.J.*, **730**, L27. (doi:10.1088/2041-8205/730/2/L27)
- Ofman, L. 2005 MHD Waves and Heating in Coronal Holes. *Space Science Rev.*, **120**, 67–94. (doi:10.1007/s11214-005-5098-1)



- Ofman, L. 2009 Progress, Challenges, and Perspectives of the 3D MHD Numerical Modeling of Oscillations in the Solar Corona. *Space Science Rev.*, **149**, 153–174. (doi:10.1007/s11214-009-9501-1)
- Ofman, L. 2010 Wave Modeling of the Solar Wind. *Living Reviews in Solar Physics*, **7**, 4.
- Ofman, L. & Davila, J. M. 1998 Solar wind acceleration by large-amplitude non-linear waves: Parametric study. *J. Geophys. Res.*, **103**, 23 677–23 690. (doi:10.1029/98JA01996)
- Ofman, L., Nakariakov, V. M. & Sehgal, N. 2000 Dissipation of Slow Magnetosonic Waves in Coronal Plumes. *Astrophys.J.*, **533**, 1071–1083. (doi:10.1086/308691)
- Ofman, L., Romoli, M., Poletto, G., Noci, G. & Kohl, J. L. 1997 Ultraviolet Coronagraph Spectrometer Observations of Density Fluctuations in the Solar Wind. *Astrophys.J.*, **491**, L111. (doi:10.1086/311067)
- Ofman, L. & Sui, L. 2006 Oscillations of Hard X-Ray Flare Emission Observed by RHESSI: Effects of Super-Alfvénic Beams? *Astrophys.J.*, **644**, L149–L152. (doi:10.1086/505622)
- Okamoto, T. J., Tsuneta, S., Berger, T. E., Ichimoto, K., Katsukawa, Y., Lites, B. W., Nagata, S., Shibata, K., Shimizu, T. *et al.* 2007 Coronal Transverse Magnetohydrodynamic Waves in a Solar Prominence. *Science*, **318**, 1577–. (doi:10.1126/science.1145447)
- Oliver, R. 2009 Prominence Seismology Using Small Amplitude Oscillations. *Space Science Rev.*, **149**, 175–197. (doi:10.1007/s11214-009-9527-4)
- O’Shea, E., Banerjee, D. & Doyle, J. G. 2006 Magnetoacoustic wave propagation in off-limb polar regions. *Astron. Astrophys.*, **452**, 1059–1068. (doi:10.1051/0004-6361:20053687)
- Pascoe, D. J., de Moortel, I. & McLaughlin, J. A. 2009*a* Impulsively generated oscillations in a 3D coronal loop. *Astron. Astrophys.*, **505**, 319–327. (doi:10.1051/0004-6361/200912270)
- Pascoe, D. J., Nakariakov, V. M., Arber, T. D. & Murawski, K. 2009*b* Sausage oscillations in loops with a non-uniform cross-section. *Astron. Astrophys.*, **494**, 1119–1125. (doi:10.1051/0004-6361:200810541)
- Pascoe, D. J., Wright, A. N. & De Moortel, I. 2010 Coupled Alfvén and Kink Oscillations in Coronal Loops. *Astrophys.J.*, **711**, 990–996. (doi:10.1088/0004-637X/711/2/990)
- Pascoe, D. J., Wright, A. N. & De Moortel, I. 2011 Propagating Coupled Alfvén and Kink Oscillations in an Arbitrary Inhomogeneous Corona. *Astrophys.J.*, **731**, 73. (doi:10.1088/0004-637X/731/1/73)
- Peter, H. 2010 Asymmetries of solar coronal extreme ultraviolet emission lines. *Astron. Astrophys.*, **521**, A51. (doi:10.1051/0004-6361/201014433)

- Roberts, B., Edwin, P. M. & Benz, A. O. 1984 On coronal oscillations. *Astrophys.J.*, **279**, 857–865. (doi:10.1086/161956)
- Roupe van der Voort, L., Leenaarts, J., de Pontieu, B., Carlsson, M. & Vissers, G. 2009 On-disk Counterparts of Type II Spicules in the Ca II 854.2 nm and H $\alpha$  Lines. *Astrophys.J.*, **705**, 272–284. (doi:10.1088/0004-637X/705/1/272)
- Ruderman, M. S. 2011 Transverse Oscillations of Coronal Loops with Slowly Changing Density. *Solar Phys.*, **271**, 41–54. (doi:10.1007/s11207-011-9772-z)
- Ruderman, M. S. & Erdélyi, R. 2009 Transverse Oscillations of Coronal Loops. *Space Science Rev.*, **149**, 199–228. (doi:10.1007/s11214-009-9535-4)
- Ruderman, M. S., Nakariakov, V. M. & Roberts, B. 1998 Alfven wave phase mixing in two-dimensional open magnetic configurations. *Astron. Astrophys.*, **338**, 1118–1124.
- Ruderman, M. S. & Roberts, B. 2002 The Damping of Coronal Loop Oscillations. *Astrophys.J.*, **577**, 475–486. (doi:10.1086/342130)
- Sakao, T., Kano, R., Narukage, N., Kotoku, J., Bando, T., DeLuca, E. E., Lundquist, L. L., Tsuneta, S., Harra, L. K. *et al.* 2007 Continuous Plasma Outflows from the Edge of a Solar Active Region as a Possible Source of Solar Wind. *Science*, **318**, 1585–. (doi:10.1126/science.1147292)
- Schrijver, C. J., Aschwanden, M. J. & Title, A. M. 2002 Transverse oscillations in coronal loops observed with TRACE I. An Overview of Events, Movies, and a Discussion of Common Properties and Required Conditions. *Solar Phys.*, **206**, 69–98. (doi:10.1023/A:1014957715396)
- Schrijver, C. J., Title, A. M., Berger, T. E., Fletcher, L., Hurlburt, N. E., Nightingale, R. W., Shine, R. A., Tarbell, T. D., Wolfson, J. *et al.* 1999 A new view of the solar outer atmosphere by the Transition Region and Coronal Explorer. *Solar Phys.*, **187**, 261–302. (doi:10.1023/A:1005194519642)
- Selwa, M. & Ofman, L. 2010 The Role of Active Region Topology in Excitation, Trapping, and Damping of Coronal Loop Oscillations. *Astrophys.J.*, **714**, 170–177. (doi:10.1088/0004-637X/714/1/170)
- Selwa, M., Ofman, L. & Solanki, S. K. 2011*a* The Role of Active Region Loop Geometry. I. How Can it Affect Coronal Seismology? *Astrophys.J.*, **726**, 42. (doi:10.1088/0004-637X/726/1/42)
- Selwa, M., Solanki, S. K. & Ofman, L. 2011*b* The Role of Active Region Loop Geometry. II. Symmetry Breaking in Three-dimensional Active Region: Why are Vertical Kink Oscillations Observed so Rarely? *Astrophys.J.*, **728**, 87. (doi:10.1088/0004-637X/728/2/87)
- Soler, R., Oliver, R. & Ballester, J. L. 2011*a* Spatial Damping of Propagating Kink Waves in Prominence Threads. *Astrophys.J.*, **726**, 102. (doi:10.1088/0004-637X/726/2/102)

- Soler, R., Terradas, J. & Goossens, M. 2011*b* Spatial Damping of Propagating Kink Waves Due to Resonant Absorption: Effect of Background Flow. *Astrophys.J.*, **734**, 80. (doi:10.1088/0004-637X/734/2/80)
- Soler, R., Terradas, J., Verth, G. & Goossens, M. 2011*c* Resonantly Damped Propagating Kink Waves in Longitudinally Stratified Solar Waveguides. *Astrophys.J.*, **736**, 10. (doi:10.1088/0004-637X/736/1/10)
- Suzuki, T. K. & Inutsuka, S.-i. 2005 Making the Corona and the Fast Solar Wind: A Self-consistent Simulation for the Low-Frequency Alfvén Waves from the Photosphere to 0.3 AU. *Astrophys.J.*, **632**, L49–L52. (doi:10.1086/497536)
- Taroyan, Y. & Erdélyi, R. 2009 Heating Diagnostics with MHD Waves. *Space Science Rev.*, **149**, 229–254. (doi:10.1007/s11214-009-9506-9)
- Terradas, J. 2009 Excitation of Standing Kink Oscillations in Coronal Loops. *Space Science Rev.*, **149**, 255–282. (doi:10.1007/s11214-009-9560-3)
- Terradas, J., Arregui, I., Verth, G. & Goossens, M. 2011 Seismology of Transversely Oscillating Coronal Loops with Siphon Flows. *Astrophys.J.*, **729**, L22. (doi:10.1088/2041-8205/729/2/L22)
- Terradas, J., Goossens, M. & Verth, G. 2010 Selective spatial damping of propagating kink waves due to resonant absorption. *Astron. Astrophys.*, **524**, A23. (doi:10.1051/0004-6361/201014845)
- Tian, H., McIntosh, S. W. & De Pontieu, B. 2011 The Spectroscopic Signature of Quasi-periodic Upflows in Active Region Timeseries. *Astrophys.J.*, **727**, L37. (doi:10.1088/2041-8205/727/2/L37)
- Tomczyk, S. & McIntosh, S. W. 2009 Time-Distance Seismology of the Solar Corona with CoMP. *Astrophys.J.*, **697**, 1384–1391. (doi:10.1088/0004-637X/697/2/1384)
- Tomczyk, S., McIntosh, S. W., Keil, S. L., Judge, P. G., Schad, T., Seeley, D. H. & Edmondson, J. 2007 Alfvén Waves in the Solar Corona. *Science*, **317**, 1192–. (doi:10.1126/science.1143304)
- Tripathi, D., Isobe, H. & Jain, R. 2009 Large Amplitude Oscillations in Prominences. *Space Science Rev.*, **149**, 283–298. (doi:10.1007/s11214-009-9583-9)
- Tsiklauri, D. & Nakariakov, V. M. 2001 Wide-spectrum slow magnetoacoustic waves in coronal loops. *Astron. Astrophys.*, **379**, 1106–1112. (doi:10.1051/0004-6361:20011378)
- Uchida, Y. 1970 Diagnosis of Coronal Magnetic Structure by Flare-Associated Hydromagnetic Disturbances. *Pub. Astron. Soc. Japan*, **22**, 341.
- Ugarte-Urra, I. & Warren, H. P. 2011 Temporal Variability of Active Region Outflows. *Astrophys.J.*, **730**, 37. (doi:10.1088/0004-637X/730/1/37)
- Van Doorselaere, T., Brady, C. S., Verwichte, E. & Nakariakov, V. M. 2008*a* Seismological demonstration of perpendicular density structuring in the solar corona. *Astron. Astrophys.*, **491**, L9–L12. (doi:10.1051/0004-6361:200810659)

- Van Doorselaere, T., Nakariakov, V. M. & Verwichte, E. 2008*b* Detection of Waves in the Solar Corona: Kink or Alfvén? *Astrophys.J.*, **676**, L73–L75. (doi:10.1086/587029)
- Van Doorselaere, T., Wardle, N., Del Zanna, G., Jansari, K., Verwichte, E. & Nakariakov, V. M. 2011 The First Measurement of the Adiabatic Index in the Solar Corona Using Time-dependent Spectroscopy of Hinode/EIS Observations. *Astrophys.J.*, **727**, L32. (doi:10.1088/2041-8205/727/2/L32)
- Vasheghani Farahani, S., Nakariakov, V. M., van Doorselaere, T. & Verwichte, E. 2011 Nonlinear long-wavelength torsional Alfvén waves. *Astron. Astrophys.*, **526**, A80. (doi:10.1051/0004-6361/201016063)
- Vasheghani Farahani, S., Van Doorselaere, T., Verwichte, E. & Nakariakov, V. M. 2009 Propagating transverse waves in soft X-ray coronal jets. *Astron. Astrophys.*, **498**, L29–L32. (doi:10.1051/0004-6361/200911840)
- Verth, G. & Erdélyi, R. 2008 Effect of longitudinal magnetic and density inhomogeneity on transversal coronal loop oscillations. *Astron. Astrophys.*, **486**, 1015–1022. (doi:10.1051/0004-6361:200809626)
- Verth, G., Erdélyi, R. & Jess, D. B. 2008 Refined Magnetoseismological Technique for the Solar Corona. *Astrophys.J.*, **687**, L45–L48. (doi:10.1086/593184)
- Verth, G., Goossens, M. & He, J.-S. 2011 Magnetoseismological Determination of Magnetic Field and Plasma Density Height Variation in a Solar Spicule. *Astrophys.J.*, **733**, L15. (doi:10.1088/2041-8205/733/1/L15)
- Verth, G., Terradas, J. & Goossens, M. 2010 Observational Evidence of Resonantly Damped Propagating Kink Waves in the Solar Corona. *Astrophys.J.*, **718**, L102–L105. (doi:10.1088/2041-8205/718/2/L102)
- Verth, G., Van Doorselaere, T., Erdélyi, R. & Goossens, M. 2007 Spatial magneto-seismology: effect of density stratification on the first harmonic amplitude profile of transversal coronal loop oscillations. *Astron. Astrophys.*, **475**, 341–348. (doi:10.1051/0004-6361:20078086)
- Verwichte, E., Aschwanden, M. J., Van Doorselaere, T., Foullon, C. & Nakariakov, V. M. 2009 Seismology of a Large Solar Coronal Loop from EUVI/STEREO Observations of its Transverse Oscillation. *Astrophys.J.*, **698**, 397–404. (doi:10.1088/0004-637X/698/1/397)
- Verwichte, E., Marsh, M., Foullon, C., Van Doorselaere, T., De Moortel, I., Hood, A. W. & Nakariakov, V. M. 2010 Periodic Spectral Line Asymmetries in Solar Coronal Structures from Slow Magnetoacoustic Waves. *Astrophys.J.*, **724**, L194–L198. (doi:10.1088/2041-8205/724/2/L194)
- Walsh, R. W. & Ireland, J. 2003 The heating of the solar corona. *Astron. Astrophys.r*, **12**, 1–41. (doi:10.1007/s00159-003-0021-9)
- Wang, T. 2011 Standing Slow-Mode Waves in Hot Coronal Loops: Observations, Modeling, and Coronal Seismology. *Space Science Rev.*, **158**, 397–419. (doi:10.1007/s11214-010-9716-1)

- Wang, T., Ofman, L. & Davila, J. M. 2011 Propagating Intensity Disturbances in Fan-like Coronal Loops: Flows or Waves? *ArXiv e-prints*.
- Wang, T. J., Ofman, L. & Davila, J. M. 2009a Propagating Slow Magnetoacoustic Waves in Coronal Loops Observed by Hinode/EIS. *Astrophys.J.*, **696**, 1448–1460. (doi:10.1088/0004-637X/696/2/1448)
- Wang, T. J., Ofman, L., Davila, J. M. & Mariska, J. T. 2009b Hinode/EIS observations of propagating low-frequency slow magnetoacoustic waves in fan-like coronal loops. *Astron. Astrophys.*, **503**, L25–L28. (doi:10.1051/0004-6361/200912534)
- Warren, H. P., Ugarte-Urra, I., Young, P. R. & Stenborg, G. 2011 The Temperature Dependence of Solar Active Region Outflows. *Astrophys.J.*, **727**, 58. (doi:10.1088/0004-637X/727/1/58)
- Wills-Davey, M. J. & Attrill, G. D. R. 2009 EIT Waves: A Changing Understanding over a Solar Cycle. *Space Science Rev.*, **149**, 325–353. (doi:10.1007/s11214-009-9612-8)
- Winebarger, A. R., Warren, H., van Ballegooijen, A., DeLuca, E. E. & Golub, L. 2002 Steady Flows Detected in Extreme-Ultraviolet Loops. *Astrophys.J.*, **567**, L89–L92. (doi:10.1086/339796)
- Zaitsev, V. V. & Stepanov, A. V. 2008 REVIEWS OF TOPICAL PROBLEMS: Coronal magnetic loops. *Physics Uspekhi*, **51**, 1123–1160. (doi:10.1070/PU2008v051n11ABEH006657)
- Zaitsev, V. V. & Stepanov, A. V. 1975 On the origin of pulsations of type IV solar radio emission. Plasma cylinder oscillations (I). *Issledovaniia Geomagnetizmu Aeronomii i Fizike Solntsa*, **37**, 3–10.
- Zaqarashvili, T. V. & Erdélyi, R. 2009 Oscillations and Waves in Solar Spicules. *Space Science Rev.*, **149**, 355–388. (doi:10.1007/s11214-009-9549-y)
- Zimovets, I. V. & Struminsky, A. B. 2009 Imaging Observations of Quasi-Periodic Pulsatory Nonthermal Emission in Two-Ribbon Solar Flares. *Solar Phys.*, **258**, 69–88. (doi:10.1007/s11207-009-9394-x)